# A LEAKAGE MODEL OF POSTHARVEST STORAGE FACILITIES


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**ABSTRACT**

A leakage model to describe gas transport between postharvest storage facilities and their environment was developed. The model assumed the gas flow to be proportional to the pressure difference between the storage facility and the environment. A protocol was developed to perform a standardized leakage test to define a specific value for the leakiness of the storage facility which is independent of storage facility characteristics and allows comparison. The proposed methodology allows not only to estimate the leakage before start of the storage season, but allows to estimate and monitor the leakiness of the facility after loading of the fruit throughout the storage season. The model was experimentally validated in controlled atmosphere conditions in which different kinds of known leaks were induced in an empty gastight storage container. The model was able to predict the measured pressure changes accurately for all induced leakages.



Keywords: Leakiness, Leakage test, Gas flow, Controlled atmosphere


## 1. INTRODUCTION

Apple fruit (*Malus × domestica borkh.*) is often stored under controlled atmosphere (CA) conditions and at low temperature to prevent fast senescence and quality loss of the fruit (Ho et al., 2013). With CA storage, fruits are stored at a decreased oxygen and an increased carbon dioxide partial pressure. These measures are meant to slow down the biochemical process of fruit respiration, which leads to quality loss and finally decay of the stored fruit (Verboven et al., 2006). However, oxygen partial pressures in the storage facility should not be lower than the lower oxygen limit of the fruit i.e. the oxygen concentration at which flavor and storage disorders tend to develop (Franck et al., 2007; Wright et al., 2010; Yearsley et al., 1996). Optimal storage conditions are determined in an empirical way. To be able to maintain the necessary low oxygen levels, the storage facility needs to be gastight.

In this paper, a mathematical model to describe the exchange of gasses between storage facility and environment is developed and validated using experiments in controlled conditions. A methodology is presented to determine the leakiness of storage facilities combining the model with measurements of the storage room pressure drop dynamics. With the proposed methodology, leakiness of storage facilities can be compared regardless their dimensions.

## 2. MATERIALS AND METHODS

### 2.1 System model

Consider a typical storage facility system as shown in Figure 1 consisting of a coolroom filled with fruit destined for consumption after a certain period of storage. Due to the low temperatures which are typical for postharvest storage and water loss by the stored produce, the relative humidity of the controlled atmosphere will be close to 100%. It follows from the Mollier diagram that the partial pressure of water vapor will be less than 0.6 kPa. Therefore, one can assume the gas inside the coolroom consists only of oxygen, carbon dioxide and nitrogen gas with respective number of moles $n_{O2,r}$, $n_{CO2,r}$ and $n_{N2,r}$. The free volume of the coolroom is given by $V$ [m$^3$] and the pressure inside the room is given by $P$ [Pa]. The environment of the coolroom is assumed to be at atmospheric conditions. The atmospheric air pressure is given by $P_a$.

Changes in gas conditions are mainly caused by fruit respiration. However, the storage facility is not perfectly gastight, allowing gas flows between the storage facility and the environment. The gas flows of oxygen, carbon dioxide and nitrogen gas are given by $q_{O2}$, $q_{CO2}$ and $q_{N2}$ respectively. Gas transport was assumed to be pressure driven. The rate of change of the number of moles of the relevant gasses in the storage facility is then given by:

$$\begin{cases} \frac{\partial n_{O_2}}{\partial t} = -r_{O_2} M + q_{O_2} \\ \frac{\partial n_{CO_2}}{\partial t} = r_{CO_2} M + q_{CO_2} \\ \frac{\partial n_{N_2}}{\partial t} = q_{N_2} \end{cases} \tag{1}$$

with $\frac{\partial n_i}{\partial t}$ the rate of change of the number of moles of gas component $i$ in the storage facility [mol s$^{-1}$], $r_{O_2}$ the rate of oxygen consumption by the fruit [mol kg$^{-1}$ s$^{-1}$], $r_{CO_2}$ the rate of carbon dioxide production by the fruit [mol kg$^{-1}$ s$^{-1}$], $M$ the mass of the stored fruit [kg] and $q_i$ the gas flow of component $i$ due to leakage [mol s$^{-1}$].

The pressure in the storage facility can then be calculated as:

$$P = \sum_i n_i \frac{RT}{V} \tag{2}$$

with $P$ the pressure [Pa], $R$ the universal gas constant [J mol$^{-1}$ K$^{-1}$], $T$ the temperature of the air in the storage facility [K] and $V$ the volume of the facility [m$^3$].

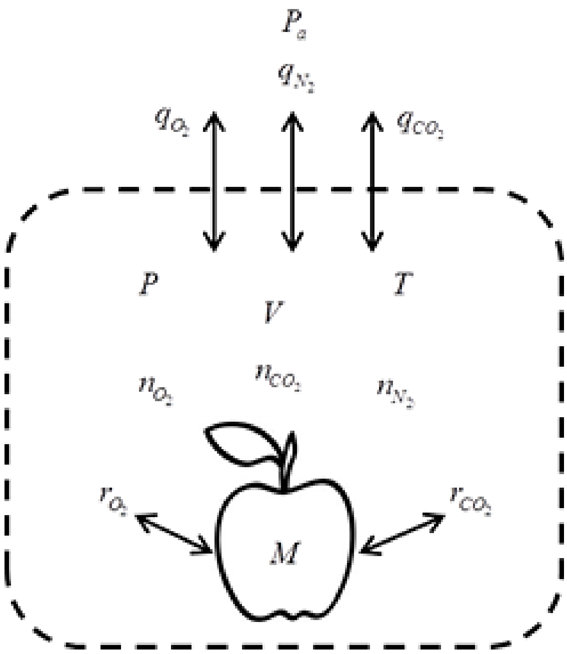


Figure 1: Schematic representation of a storage facility and its environment.

### 2.2 Pressure driven leakage model formulation

A leakage model describing pressure driven gas transport between storage facility and environment was developed. The gas flow between storage facility and environment was assumed to be proportional with the pressure difference between the inside and outside of the storage facility. The rate of change of the number of moles gas in the storage facility due to pressure driven leakage is given by:

$$q = -k\left(P - P_a\right) \tag{3}$$

with $q$ the rate of change of the total number of moles in the storage facility [mol $s^{-1}$], $k$ the leakage constant of the storage facility [mol $s^{-1}$ $Pa^{-1}$], $P$ the pressure of the storage facility [Pa], $P_a$ pressure of the atmosphere [Pa].

### 2.3 Leakage test development

Eq. (3) can be rewritten using the ideal gas law and integrated over time, assuming the atmospheric air pressure to be constant. This leads to:

$$\ln\left(\frac{P_f - P_a}{P_i - P_a}\right) = -\frac{k}{V}\left(t - t_0\right)RT \tag{4}$$

with *ln* the natural logarithm, $P_a$ the atmospheric air pressure [Pa], $P_i$ the initial pressure in the storage facility, $P_f$ the final pressure in the storage facility [Pa], $k$ the leakage constant of the storage facility [mol $s^{-1}$ $Pa^{-1}$], $V$ the free volume of the storage facility [$m^3$], $R$ the ideal gas constant equal to 8.314 [J $mol^{-1}$ $K^{-1}$], $T$ the temperature [K], $t$ the time [s] and $t_0$ the initial time [s].

Eq. (4) allows one to perform an experiment to determine the leakage constant of the storage facility by pressurizing the system and monitoring the pressure drop as a function of time while taking note of the atmosphere pressure. One can subsequently calculate the ratio of $k/V$ of the storage facility which can be used as a standardized parameter to compare storage facilities regardless their volume or degree of filling. It describes the number of moles of gas that will enter or leave the storage facility per second of time per Pa pressure difference between the storage facility and its environment per $m^3$ of free volume in the room. Therefore in all storage facilities with the same $k/V$ ratio, the effect of leakage on gas changes in the facility will be the same making it a good parameter for comparison.

### 2.4 Leakage model parameter estimation and model validation

#### 2.4.1 Model parameter estimation

An experimental setup using an empty gastight HDPE storage container with dimensions of 0.88 m length, 0.58 m width and 0.58 m height was used. The top of the container was provided with a gutter which was filled with water and in which the top lid of the container was placed to ensure gastightness as shown in Figure 2. A weight of 10 kg was put on top of the lid of the container to avoid floating and to ensure the volume in the container remained constant throughout the experiment. The storage container was placed in a cold room of 1 °C. Three experimental conditions were tested. In the first condition, no additional leakage was induced to the storage container, while with the other conditions an artificial leak was induced by placing a polyurethane tube (FESTO N.V., Belgium) with an internal diameter of 3 mm and 6 mm respectively and a length of 76 cm trough the water lock of the container. To prevent the top lid squeezing the gas tube, the gas tube was led through a wooden block which was put underneath the top lid of the container (see Figure 2). For each of the conditions, a pressure test was conducted and repeated 3 times to estimate the leakage constant of the container in the three leakage states. Therefore, the container was pressurized by injecting $N_2$ through a tube with an internal diameter of 6 mm different from the one to induce the leakage. A flow rate of 2 L.$s^{-1}$, from a pressurized cylinder (Air Liquide N.V., Belgium) was used to overpressure the container with 150 Pa. . Subsequently the pressure drop in the container was monitored as a function of time. Container as well as atmosphere pressure were measured every minute using a digital pressure sensor (MEAS MS5611-01BA03, MEAS, Switzerland) with an accuracy of 1 Pa.

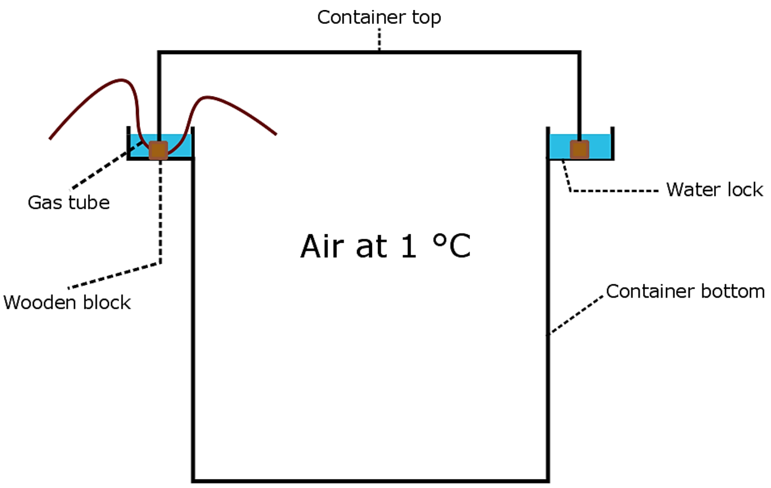


Figure 2: Schematic representation of the experimental setup used.

#### 2.4.2 Model validation

The pressure driven gas flow $q$ between the storage container and environment as predicted by the leakage model represented by eq. (3) was indirectly validated. Validation experiments were carried out for each of the three experimental leakage setups (no induced leakage and leakage induced with a gas tubing of 3 mm and 6 mm internal diameter respectively). For each of the setups, container pressure was monitored for a time period of 350 minutes along with atmospheric pressure during an increasing as well as during a decreasing atmospheric pressure period. Finally, for each setup, the leakage model and the estimated $k$ values were used to simulate the pressure inside the storage container for a time period of 350 minutes using Matlab (MathWorks Inc., USA), based on initial container pressure and measured atmospheric pressure for each of the three setups used.

## 3. RESULTS AND DISCUSSION

### 3.1 Pressure drop experiment

It was needed that the created overpressure during the test was high enough to be accurately measurable, but should not be too high, causing plastic deformation of the storage container that would result in an over estimation of the leakage constant $k$ or would damage the container. An optimal value of overpressure during the test was found to be 150 Pa. This value is safe and will not cause any mechanical damage to the storage facility. An example of one of the pressure drop experiments is shown in Figure 3 (a). To validate the assumption that the gas flow and thus the change of pressure over time is proportional to the pressure difference between the inside and outside of the container and shows an exponential decay, the natural logarithm of the pressure difference was plotted as a function of time as shown in Figure 3 (b). As one can see, there is a strong linear relationship between $ln(\Delta P)$ and $t$, proving the pressure exponentially drops in the storage container.
Table 1 shows the estimated ratios of $k/V$ of the different storage container setups based on three repeated pressure drop experiments for three different experimental conditions. It can be seen that consistent and repeatable measurements were obtained. However, the larger the leakage becomes, the larger the variation in estimated $k/V$ values will be. Mean values of these estimations were used in the model to predict changes in container pressure due to leakage in the validation experiments discussed in the following sections.

Since the $k/V$ ratio [mol $s^{-1}$ $Pa^{-1}$ $m^{-3}$] represents the number of moles of gas that enters or leaves the storage facility per second per Pa pressure difference per $m^3$ free volume in the storage facility, it is a good measure of the relative leakiness of the facility which allows comparison. Namely, in all storage facilities with the same $k/V$ ratio, leakage will have the same concentration change effect.

Furthermore, using $k/V$ as a leakage parameter has the advantage that the free volume of the storage facility does not need to be known since $k/V$ can be determined directly using eq. (4). Although in this paper the determination of $k/V$ has only been illustrated for an empty storage container with different induced leakages, it can be determined in any commercial system using the same experimental approach.

This allows one to determine the $k/V$ ratio as well as absolute leakage $k$ [mol $s^{-1}$ $Pa^{-1}$] of the storage facility at the beginning of the storage season when the room is not loaded (free volume is known). Due to the very high diffusivities of $N_2$, $O_2$ and $CO_2$ in air, the stacking pattern in the room will have little influence on the gas transport. Furthermore, $k/V$ can be calculated after loading of the room as well as throughout the storage season to monitor the evolution of the relative leakiness during storage.

Critical values for $k/V$ to determine if a certain storage room is suitable for storage of a certain produce can be formulated based on the storage temperature and respiration rate of a certain produce according to eq. (5):

$$\Delta P \cdot \frac{k}{V} \leq r_P^{Opt} \tag{5}$$

With $\Delta P$ the typical pressure difference between the storage facility and environment [Pa], $k$ the leakage constant of the storage facility [mol $s^{-1}$ $Pa^{-1}$], $V$ the free volume of the storage facility [$m^3$] and $r_P^{Opt}$ the product specific respiration rate at the optimal storage temperature and gas conditions [mol $s^{-1}$ $m^{-3}$].

Table 1: Estimated ratio of $k/V$ [mol $s^{-1}$ $Pa^{-1}$ $m^{-3}$] for three different amounts of leakage in the empty storage container.

| **Trial – Induced leakage** | **0 mm** | **3 mm** | **6 mm** |
|---|---|---|---|
| **1** | $2.26 \times 10^{-5}$ | $2.66 \times 10^{-5}$ | $3.38 \times 10^{-5}$ |
| **2** | $2.25 \times 10^{-5}$ | $3.08 \times 10^{-5}$ | $4.47 \times 10^{-5}$ |
| **3** | $2.23 \times 10^{-5}$ | $2.67 \times 10^{-5}$ | $3.85 \times 10^{-5}$ |

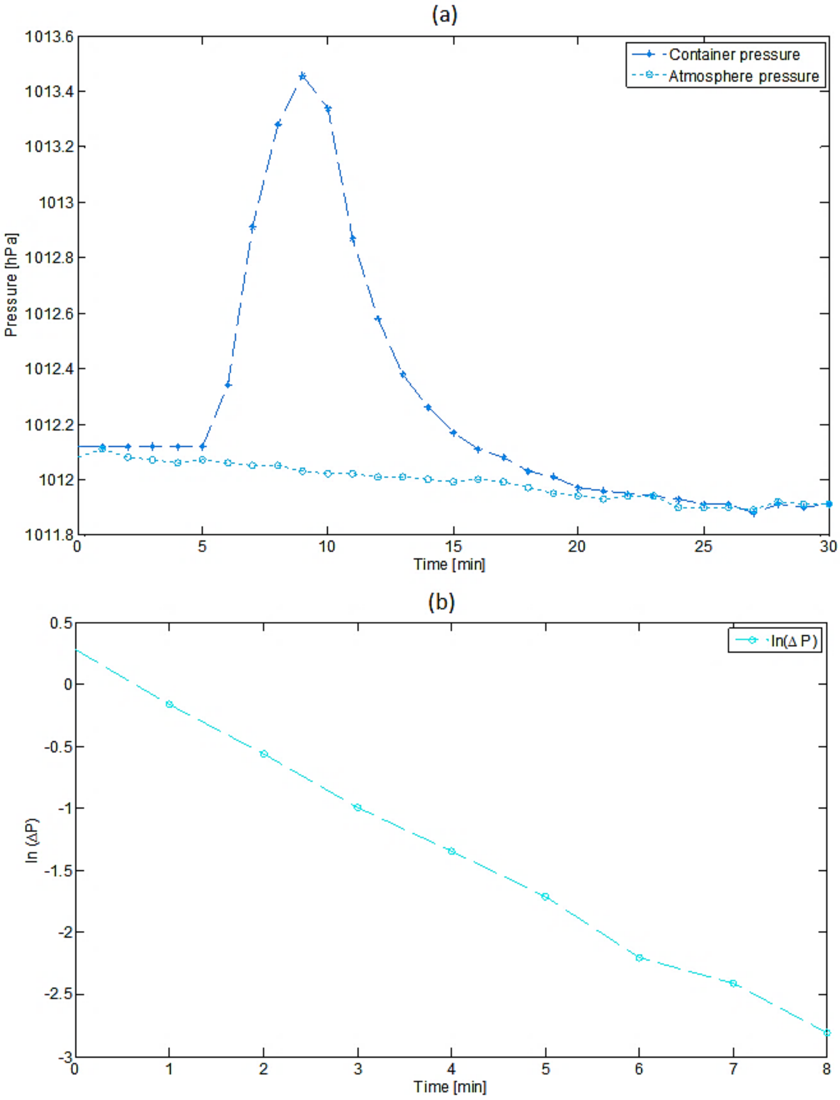


Figure 3: (a) An example of one of the pressure drop experiments in which the storage container is pressurized to an overpressure of 150 Pa followed by an exponential pressure decay and (b) natural logarithm of the pressure difference as a function of time.

### 3.2 Validation experiments

Figure 4 shows the measured versus simulated container pressure as a function of time for the validation experiment without induced leakage and for the validation experiment in which an additional leakage was induced with a gas tube of 6 mm internal diameter, respectively. Internal container and atmosphere pressure were measured for a time period of 350 minutes. Atmosphere and initial internal container pressure were used to simulate the internal container pressure as a function of time for 350 minutes. The comparison of measured an simulated container pressure are shown in Figure 4 (a) and (b) for the setup without induced leakage and a leak induced with a 6 mm internal diameter tube respectively during an increasing atmospheric pressure. For the case of a leak induced with a 6 mm diameter gas tube, results are also shown for the validation experiment during a decrease in atmosphere pressure for a time period of 240 minutes. Figure 4 (c). A close fit between measured and simulated container pressure was obtained for both the case without induce leakage and a leak induced with a 6 mm internal diameter tube during an increasing as well as a decreasing atmospheric pressure. However, small discrepancies between simulated and measured container pressure remained when the atmosphere pressure changed quickly (atmosphere pressure not shown here), indicating the obtained values for $k/V$ slightly underestimated the real value.

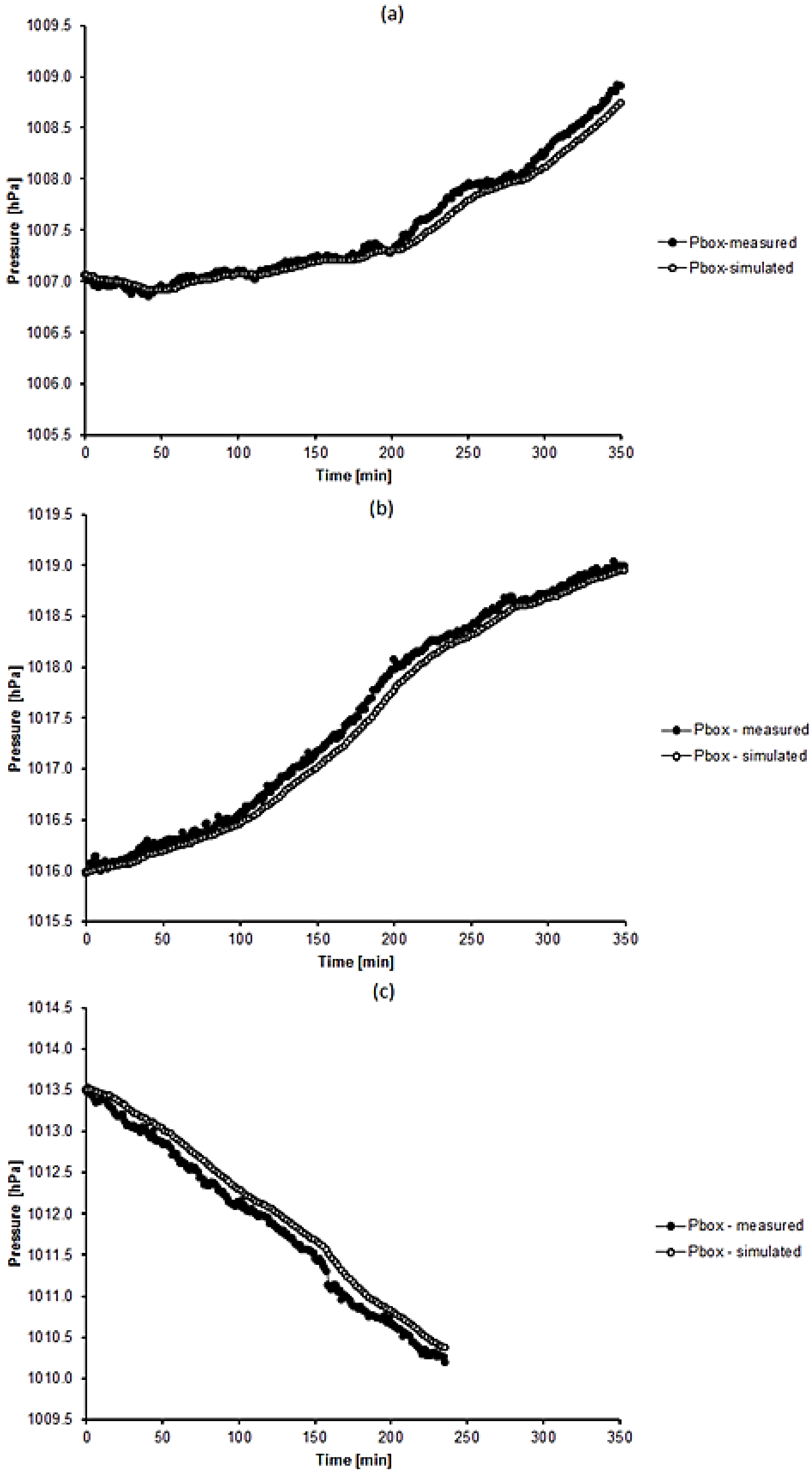


Figure 4: Measured container pressure versus simulated container pressure as a function of time for the validation experiments without induced leakage during an increasing atmospheric pressure Figure 4 (a) and for the experiment in which additional leakage was induced with a gas tube of 6 mm internal diameter during an increasing and decreasing in atmospheric pressure Figure 4 (b,c), respectively.

## 4. CONCLUSION

A leakage model to describe gas transport between postharvest storage facilities and their environment was developed. The model assumed the gas flow to be proportional to the pressure difference between the storage facility and the environment. A protocol was developed to perform a standardized leakage test to define a specific value for the leakiness of the storage facility which is independent of storage facility characteristics and allows comparison. The proposed methodology allows not only to estimate the leakage before start of the storage season, but allows to estimate and monitor the leakiness of the facility after loading of the fruit throughout the storage season. The model was experimentally validated in controlled atmosphere conditions in which different kinds of known leaks were induced in an empty gastight storage container. The model was able to predict the measured pressure changes accurately for all induced leakages. The model can be used to estimate the effect of leakage on changes in gas composition inside the storage facility.

## ACKNOWLEDGEMENTS

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## NOMENCLATURE

| | | | |
|---|---|---|---|
| CA | Controlled atmosphere | $\Delta P$ | Pressure difference (Pa) |
| $k$ | Leakage constant [mol $s^{-1}$ $Pa^{-1}$] | $q_i$ | Gas flow of gas component $i$ (mol $s^{-1}$) |
| $ln$ | Natural logarithm | $R$ | Universal gas constant (8.314 J $mol^{-1}$ $K^{-1}$) |
| $M$ | Mass of the stored fruit (kg) | $r_{O2}$ | $O_2$ consumption rate (mol $s^{-1}$ $kg^{-1}$) |
| $n_i$ | Number of moles of component i (mol) | $r_{CO2}$ | $CO_2$ production rate (mol $s^{-1}$ $kg^{-1}$) |
| $P$ | Pressure of the storage facility (Pa) | $r_P^{Opt}$ | Specific respiration rate (mol $s^{-1}$ $m^{-3}$) |
| $P_a$ | Pressure of the atmosphere (Pa) | $T$ | Temperature (K) |
| $P_i$ | Initial facility pressure (Pa) | $t$ | Time (s) |
| $P_f$ | Final facility pressure (Pa) | | |

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